Telesonar Signaling Measurements

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LONG-TERM GOAL

Advanced undersea acoustic communication (telesonar) modems will be capable of probing the transmission channel and automatically adapting signaling parameters to the channel response.[1, 2]

OBJECTIVE

This project quantifies the relative performance of telesonar signaling techniques with respect to the probed channel response, observed ocean environment, and model predictions.

APPROACH

Prior research, development and testing have concentrated on specific modem signaling techniques for channel tolerance, high bit-rate, or multi-user access.[3] Evaluating the relative performance of these signaling methods using existing data is perilous because of excessive parametric variations in the transmission medium, transmit electronics, receive electronics, receive SNR, frequency band, *etc*.

This FY99-start project pursues a systematic understanding of telesonar capability by exploring the fundamental relationships between the observed environmental conditions, the measured channel scattering function, and the realized signaling performance. We use standard oceanographic methods to quantify channel boundary (*i.e.*, seafloor and sea surface) conditions and channel medium (*i.e.*, ocean volume) properties. These environmental observations drive physics-based predictive models[4] to anticipate sound propagation effects. We minimize experimental error through the use of carefully designed navigation, transmit, receive, and record systems that provide commonality and fidelity for all signaling techniques under evaluation. We use specialized acoustic probes to directly observe the time- and frequency-dependent channel scattering function. Having thus gained empirical control of the test channel, we transmit a diverse collection of communication waveforms and tally performance achieved by real-time processing and post-mortem analysis. Sequential transmission of test waveforms provides continuity of channel conditions and justifies comparative evaluation. Acquisition of a statistically significant number of transmissions mitigates constraints of channel coherence time and provides confidence in our measurements.

Three different experiment formats each provide a fair basis for performance comparisons at different stages of modem implementation. *ModemEx* evaluates raw signaling performance using Navy-developed telesonar testbeds[5] for high-fidelity, broadband transmitting, receiving and recording.

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ModemDemo (previously called "*ModemFest*") evaluates fully integrated modem systems operated by third-party developers from industry and academia. Lastly, we are exploring the feasibility of *ModemSim* virtual testing using real-time simulation of telesonar channels.

WORK COMPLETED

In FY99 we developed philosophies and procedures for ModemEx and ModemDemo. We planned and performed ModemEx99 in conjunction with the April 1999 Sublink99 Exercise in San Diego, CA.[6] ModemDemo99 occurs November 1999 in conjunction with the Naval Oceanographic Office's AUV Demo 99 near Gulfport, MS. We have also identified five cost-effective and relevant ModemEx2000 test opportunities in conjunction with planned telesonar engineering tests.[7]

In ModemEx99, communication waveforms and probe signals were bidirectionally transmitted between an over-the-side telesonar testbed and an autonomous, bottom-deployed telesonar testbed (used with ONR 321SS permission), as depicted in Figure 1. The over-the-side testbed could broadcast a tonal at source level 186 dB (re 1 μPa at 1 meter) in the 8- to 16-kHz band, and was equipped with one receive hydrophone. The offboard testbed was capable of 180 db (re 1 μPa at 1 meter) and had four receive channels. Both systems acquired data with 16-bit resolution. These high-fidelity units acted as terminals for all ModemEx99 communication links, thereby reducing the number of free parameters.

The participating modem developers were Datasonics, Inc. (now Benthos, Inc.), Delphi Communication Systems Corp., Northeastern U. (NEU), and Woods Hole Oceanographic Inst. (WHOI). We constructed a waveform battery concatenating all contributed communication waveforms for repeated transmission in the test channels, as illustrated in Figure 2. Within the battery, each waveform was separated by one second for channel clearing, and a suite of probe signals forming a compound probe was sent before and after each developer's waveform set. We requested that waveform set contributed by a given developer include variations of a single transmit parameter (such as baud rate or convolutional coding length) from waveform to waveform. This would isolate effects of a single parameter, assuming the channel remained stable during the transmission of successive waveforms.

We sought to examine several distinct multipath conditions: 1) dominant, direct-path arrival with minimal multipath spread, 2) complex, extended multipath structure with a non-dominant direct path (phase-minimum channel), and 3) no direct path with indistinguishable, multipath arrivals indicating highly-scattered received energy. Using historical and measured environmental data, a 3-D Gaussian-beam model[8] predicted channel multipath structure during both the planning and execution stages of ModemEx99. During the experiment, we used on-site CTD data as input to the model to refine the best fixed positions of the terminals in accordance with the desired multipath structure. Model predictions indicated the range-dependent multipath structure to be experienced during the drifting events. The model also confirmed the presence of an interesting transition between a dropout/shadow zone to a single dominant arrival at 4.75 km, which we decided would make an interesting range to fix both platforms.

Figure 3 charts the ModemEx99 operating area 6 km west-southwest of San Diego in 200-m water at the well understood site of recent matched-field processing tests. Two close-range events confirmed equipment functionality and three events produced our data sets. During events 3 and 4 the surface ship drifted away from the testbed to a range just over 6 km. For event 5 the range between terminals was fixed at 4.75 km.

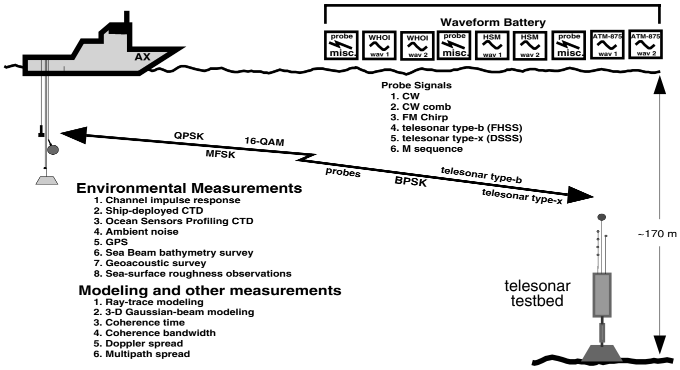

Figure 1. In ModemEx'99 a battery of communication waveforms and probe signals were bidirectionally transmitted between an over-the-side telesonar testbed and an offboard telesonar testbed.

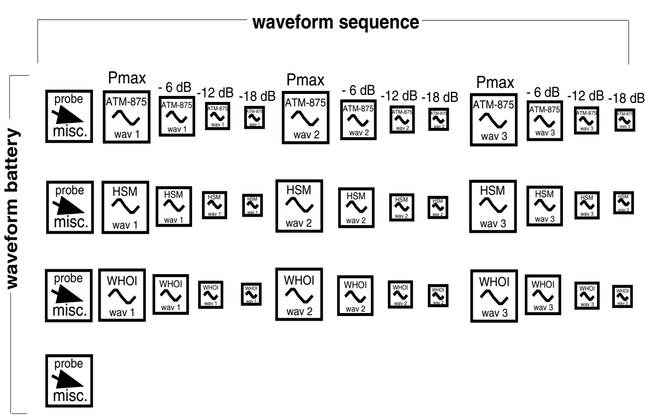

Figure 2. The waveform battery is a concatenation of many communication waveforms and compound probes. Source-level reduction producing diminishing SNR at the receiver and reveals failure modes in the demodulation and decoding process.

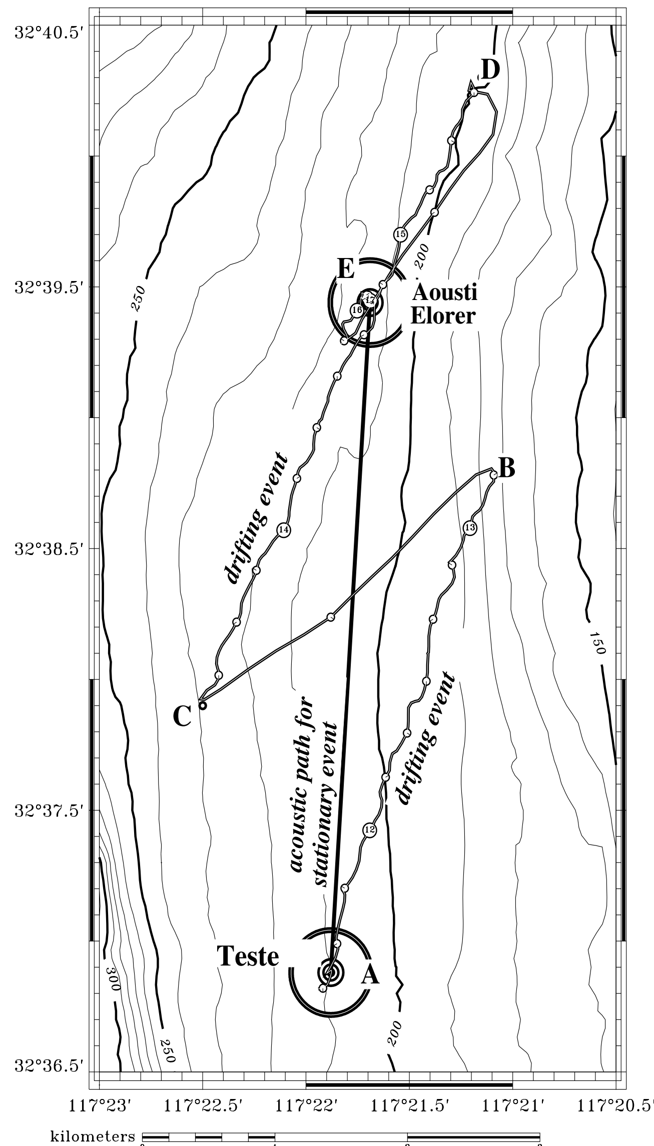

Figure 3. The offboard telesonar testbed was deployed at station A and remained there throughout the experiment. During event 3 the ship drifted from station A to waypoint B. The ship then repositioned to waypoint C. During event 4 the ship drifted from waypoint C to D. For event 5 the ship moored at station E. (Isobath contours are at 10-meter increments.)

RESULTS

ModemEx99 addressed six priorities: 1) testing both coherent and noncoherent signaling methods, 2) transmitting all signals across a common set of channels, 3) using common equipment for transmission, reception and recording, 4) characterizing the channel with frequent acoustic probes, 5) characterizing the channel with careful environmental observations, and 6) characterizing the channel with physics-based modeling.

Figure 4 shows a time series of the compound probe received by the testbed at a range approximately 1.7 km from the ship. Although the various signals within the compound probe may generate redundant information, we included them for several reasons. First, comparisons can be made among the processed probes to determine how well they correlate. Second, some of the probe signals optimally measure a particular characteristic of the channel (for example, we included a 10-s, 10-kHz sinusoid to provide high spectral resolution for determining frequency spreading and/or shifting). Third, the LFM is repeated four times within each compound probe to see how the channel changes on a time scale of seconds. Fourth, a 500-μs, 10-kHz pulse provides data for a 3-D Gaussian-beam model that assumes a similar pulse in numerical calculations.

Table 1. ModemEx99 compound probe

Probe Signal	Duration	Notes
LFM	1 s	8 - 16 kHz
Long CW	10 s	10 kHz
Short CW	40 ms	10 kHz
Very Short CW	500 µs	10 kHz
LFM	1 s	8 - 16 kHz
DS-DPSK	5 s	11 - 13 kHz
Comb	2 s	16 tones in 8 - 16 kHz band, spaced at 500 Hz
LFM	1 s	8 - 16 kHz
LFM	1 s	8 - 16 kHz

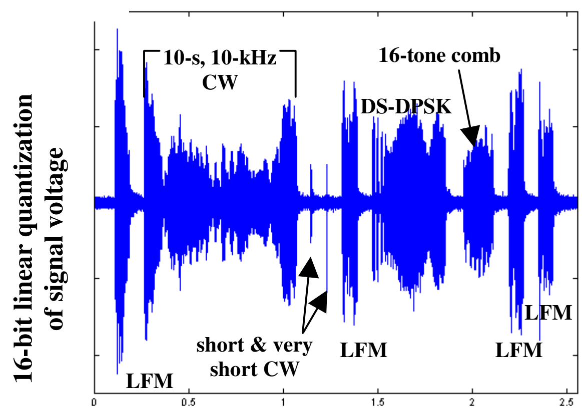

Figure 4. Compound probe received by one element of the telesonar testbed receive array at a range of 1.7 km.

ModemEx99 tested a total of seventeen signaling methods from four modem developers, as identified in Table 2. Although a complete waveform battery could not be transmitted within the channel coherence time, all signals were subjected to approximately the same channel geometry and noise, in a statistical sense. In addition, we were interested in assessing the dependence on SNR for each of the communication schemes. Each communication waveform was to be transmitted four times, decreasing the power 6 dB each time. Because this feature was not implemented in time for ModemEx99, we repeated all waveforms four times within each waveform battery at maximum power.

Datasonics and Delphi provided modems and shipboard personnel for real-time decoding of received waveforms. The first day of testing was used to prepare equipment, and obtain high-SNR recordings of the waveform battery. During set-up events 1 and 2, the modem developers successfully decoded the received waveforms with no errors, validating the sampled waveforms as well as the transmit and receive systems. During events 3 and 4, real-time decoding by Datasonics demonstrated message decoding at low SNR with zero errors at a range of approximately 4500 meters. We selected this range for more extensive measurements of the signaling methods. The ship moored at station E and we performed event 5 with fixed channel geometry for 1.5 hours.

We have analyzed the 5-hour data set and culled anomalous transmissions. The edited data set includes 1,156 communication transmissions and 68 compound-probe transmissions. Because each received waveform battery is on the order of 200 Mbytes, we have parsed each modem developer's signal sets into separate files. We established a web site describing the experiment and providing easy download access to the recorded data. Our web site displays a correlogram for the entire experiment built from the LFM probe signals and compares measured impulse response with that predicted by the 3-D Gaussian-beam model.

Table 2. ModemEx99 communication waveforms

Developer	Signaling	Notes
Datasonics	MFSK	150 bits/s, Hadamard, 1/2 rate convolutional coding, doppler tolerant, 25 ms guard band
Datasonics	MFSK	300 bits/s
Datasonics	MFSK	600 bits/s
Datasonics	MFSK	1200 bits/s
Datasonics	MFSK	2400 bits/s, (1 of 4)
Datasonics	FH-MFSK	
Delphi	QPSK	f_c = 12 kHz, bandwidth = 4 kHz
Delphi/ Datasonics	BPSK	f_c = 12 kHz, bandwidth = 4 kHz
Delphi/ Datasonics	16-QAM	f_c = 12 kHz, bandwidth = 4 kHz
NEU	DS-DPSK	10 bits/s
NEU	DS-DPSK	100 bits/s
WHOI	QPSK	pseudo-random sequence and 12/23 Golay codes for all WHOI signals. Each signaling type occupies two different frequency bands: 9.5-14.5 kHz and 8-16 kHz.
WHOI	QPSK	
WHOI	MFSK	
WHOI	MFSK	
WHOI	FH-MFSK	
WHOI	FH-MFSK	

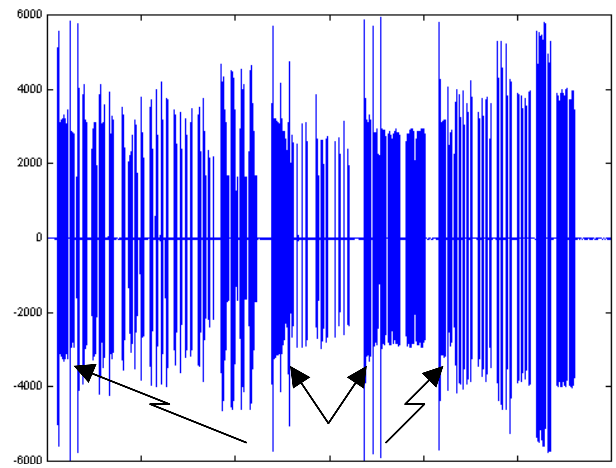

Figure 5. ModemEx99 waveform battery recorded at close range with large SNR. A compound probe is included before and after each modem developer's set of communication waveforms.

IMPACT / APPLICATIONS

ModemEx99 was a significant first experiment in a series leading to the development of a channel-adaptive, multi-mode telesonar modem. A modem pair will cooperatively probe the channel, estimate the scattering function, and automatically adjust the signaling parameters, including modulation type, information bit rate, coding, source level, spectral distribution, diversity, directivity, equalization, *etc*. These intelligent modems will exploit environmental conditions by adapting to the channel response.

TRANSITIONS

At the time of this report, we are assembling ModemEx99 post-mortem processing results from the four participating modem developers. Benthos and NEU have instituted significant improvements to their algorithms as a result of insights gained from ModemEx99. In addition, the impulse response measurements obtained from the LFM probes have helped refine the predictive power of the SSC SD ILIR 3-D Gaussian-beam model.

RELATED PROJECTS

Michael Porter and Paul Baxley were associate investigators on this project. Porter was a visiting professor from New Jersey Institute of Technology working at SSC SD on an ASEE summer sabbatical with ONR 321SS sponsorship. Baxley is an SSC SD D857 colleague funded by the SSC SD ILIR Telesonar Channel Project.

This project uses ONR 321SS telesonar testbeds, SSC SD ILIR physics-based models, and ONR 321SS and PD 18E ocean experiments. This project also relies on the participation of third-party modem developers from industry and academia, predominantly funded by ONR 32 and the Navy SBIR Program.

This project is performed as a component of the SSC SD Seaweb S&T Capabilities Initiative. Seaweb is a concept for telesonar network infrastructure linking autonomous undersea assets and including gateways to manned command centers submerged, afloat, aloft, and ashore. SSC SD has established the Seaweb Initiative as an internally funded umbrella program advancing telesonar C^4ISR. The Seaweb Initiative coordinates the following telesonar research & development efforts:

SSC-SD ILIR Telesonar Channel Project (6.1) seeks a theoretical and experimental understanding of telesonar propagation physics, including such impairments as multipath, scattering, variability, fading, attenuation, and noise.

ONR 321SS Telesonar Technology Project (6.2) develops prototype telesonar technology in the form of energy-efficient, affordable, DSP-based modems using channel-tolerant signaling for link establishment, acoustic probes for in situ channel estimation, and adaptive modulation for optimized channel capacity.

ONR 321SI DADS Network Task (6.2) applies telesonar technology for enabling the Deployable Autonomous Distributed System, a concept for wide-area undersea surveillance particularly suited for shallow-water ASW.

PD 18E Telesonar Sublink Task (6.3) integrates telesonar technology into submarine UQC-2 underwater telephone systems for digital data and digital voice links with other platforms and off-board systems.

ONR 321 Telesonar Surveillance Applications Project (6.3) advances communications infrastructure for Future Naval Capabilities in littoral ASW.

ONR 321BC NOPP Telesonar Network for FRONT Project, a component of the National Oceanographic Partnership Program, is responsible for interconnecting remote undersea sensors on the continental shelf and linking this distributed ocean observatory with the terrestrial internet via cell-phone gateway buoys.

ONR 36 SBIR Program entrusts technical oversight to SSC SD for Small-Business Innovative Research industrial contracts concerning telesonar modems (SBIR topic N93-170), telesonar networks (N97-106), and telesonar directional transducers (N99-011).

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V. K. McDonald, M. B. Porter, J. A. Rice, and P. A. Baxley, “ModemEx Philosophy,” presented at ONR 321OA High-Frequency Acoustics for Undersea Communication Workshop, Victoria, British Columbia, Canada, September 1999